

Earthquake Prediction

Because of their devastating potential, there is great interest in predicting the location and time of large earthquakes. Although a great deal is known about where earthquakes are likely to occur, there is currently no reliable way to predict the exact time that an event will occur in any specific location.

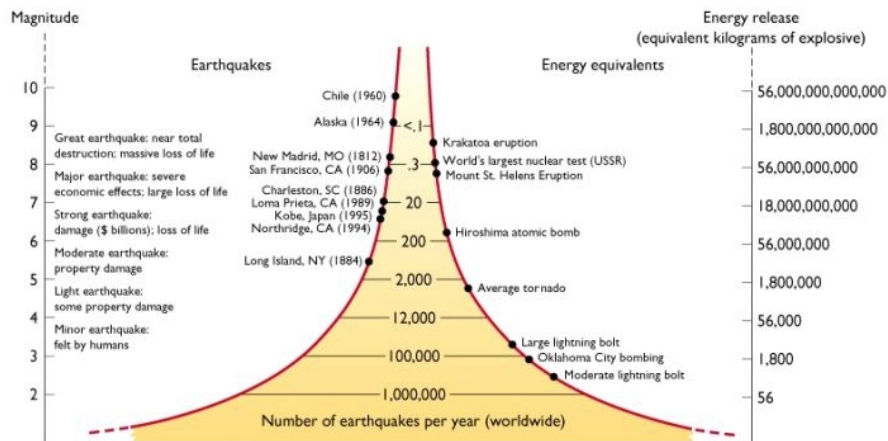
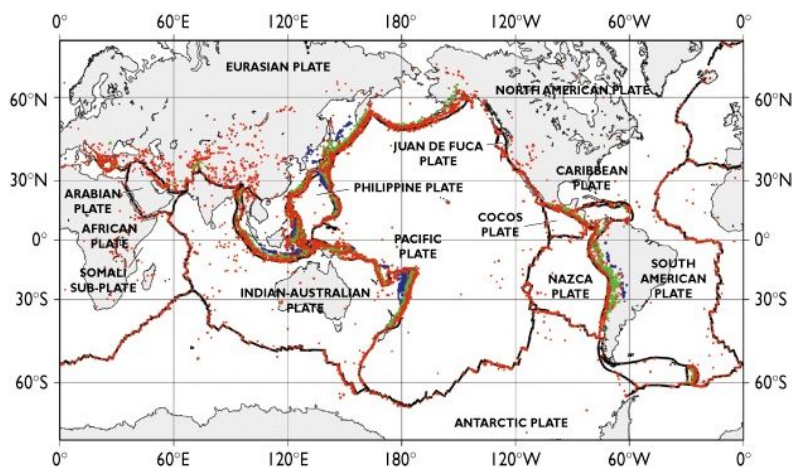


Fig. 18.11

Earthquakes through time There are about 18 major earthquakes ($M_L = 7.0-7.9$) and one great earthquake ($M_L > 8.0$) worldwide in any given year. Measurements made over the last few decades prove that the average number of quakes within each magnitude group remains roughly constant from year to year.

World Seismicity, 1963–2000

Focused around plate margins (but also seen in plate interiors)



Earthquakes Associated with Divergent and Transform Margins

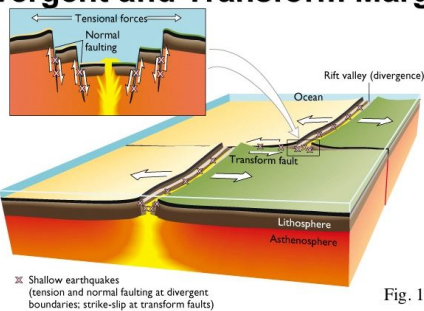


Fig. 18.15

Earthquakes Associated with Convergent Plate Margins

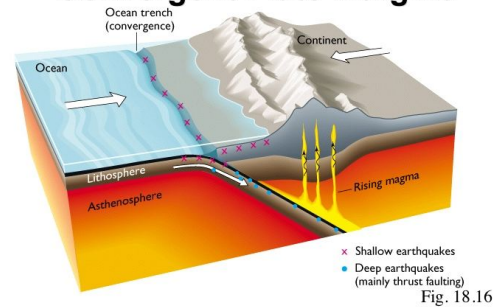


Fig. 18.16

Earthquakes and plate tectonics Earthquakes are concentrated at plate boundaries. Boundaries involving oceanic plates are characterised by narrow earthquake belts (e.g. circum-Pacific belt). Boundaries where two continental plates meet are characterised by spatially distributed earthquakes (e.g. the Arabia-Eurasia and India-Eurasia collisional zones). The reason for this behaviour is not entirely clear, but is likely related to differences in composition and thickness between oceanic and continental crust. Constructive (divergent) plate boundaries have shallow earthquakes of relatively low magnitude because mid-ocean ridges are hot, weak structures. Earthquakes of greatest magnitude occur at destructive (convergent) and transform plate boundaries.

Hazard Prediction Probabilistic ground motion maps contour earthquake ground motions that have a common probability of being exceeded in a certain period of time. They are based on historical earthquake locations and geological information on the recurrence rate of fault ruptures, and assume that the historical trends can be projected into the future.

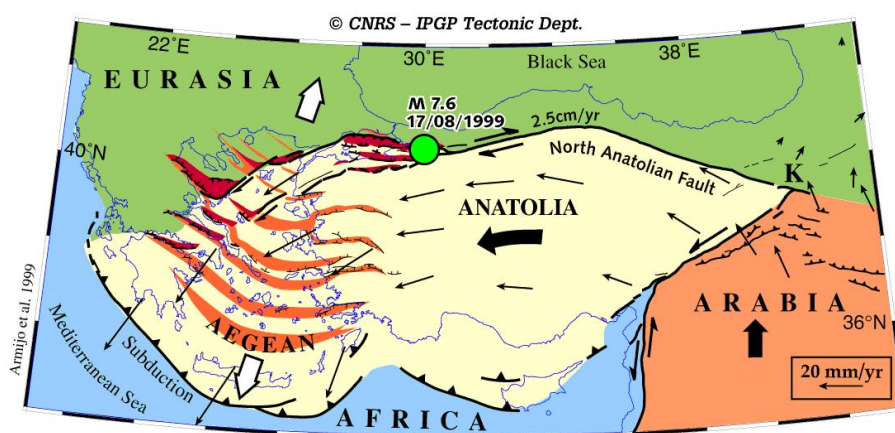
Geomorphology as a guide to fault activity Dip-slip faults (i.e. normal and thrust faults) are associated with vertical motions and produce topographic fault scarps. In an ideal world, the most recently active faults would have the highest, steepest fault scarps, allowing prediction of earthquake hazards. Unfortunately, very active, dangerous faults may have no discernable fault scarps if they cut through soft unconsolidated sediments and/or if they have only recently become active. Strike-slip faults are associated with lateral movement and often have no topographic expression. Instead, lateral offset of rivers or linear geological features can show where these faults are. Oblique-slip faults have both lateral offsets and topography.

Foreshocks Some major earthquakes, but not all, are heralded by the occurrence of foreshocks which can be detected by dense local monitoring networks. However, if a small seismic event is recorded, it is very difficult to tell whether it is just a single, low-magnitude earthquake or a foreshock to a major, high-magnitude earthquake.

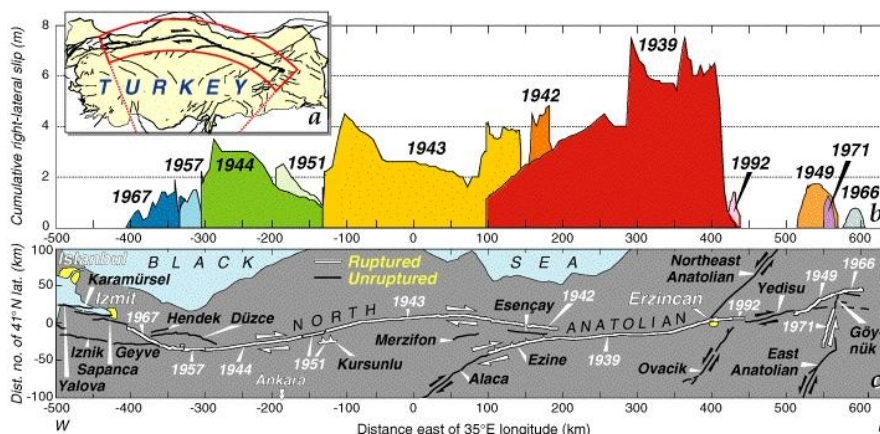
Other indicators In the periods between earthquakes, strain accumulates steadily in the general region surrounding a fault as the deep, ductile parts of the plates slip past each other continuously. This inter-earthquake deformation should cause micro-cracks to form, which should alter physical properties of the rocks. In various seismically active parts of the world, electrical and magnetic properties and changes in seismic velocity are constantly monitored in order to better understand the inter-earthquake deformation process. Such monitoring systems cannot yet predict earthquakes but it is hoped that they may be able to do so in future.

Case History: North Anatolian Fault

Summary Neither faulting nor earthquakes behaves in an isolated manner. Although an earthquake drops the average stress on the fault that slipped, it also increases the stress in certain localised regions near the fault tips. The stress increase can cause further faulting, in a process known as *stress triggering*. Probably the most successful example of earthquake prediction based on calculated stress changes is the North Anatolian Fault, Turkey. In 1997, the stress change was calculated for a westward-migrating sequence of earthquakes that have occurred since 1939. Results suggested a high probability of an earthquake in the Izmit region, and an earthquake duly occurred at Izmit in 1999. Now Istanbul is predicted to be in imminent danger.



Tectonic driving forces Motion on the North Anatolian fault is driven by rapid northward movement of Arabia into relatively stable Eurasia. Since both Arabia and Eurasia are buoyant continents, neither of them wants to subduct down into the mantle. Instead, continent-continent shortening is accommodated by the Anatolia block, which lies just south of the Black Sea, squeezing westward. GPS observations establish that the regional right-lateral motion between Eurasia and Arabia is 24 ± 4 mm/yr. Earthquakes on the North Anatolian fault are the stick-slip response of the brittle upper crust to this regional motion.



Twentieth century faulting sequence Like falling dominoes, 4 westward-migrating earthquakes ruptured 725 km of the North Anatolian fault during 1939-44, with subsequent earthquakes extending the zone of faulting eastward and westward. This classic case of progressive earthquake failure has tantalized earth scientists and terrorized insurance providers for half a century. Although clustering of earthquakes in space and time is common and migrating earthquake sequences have occurred elsewhere, none is as spectacular as on the North Anatolian fault.

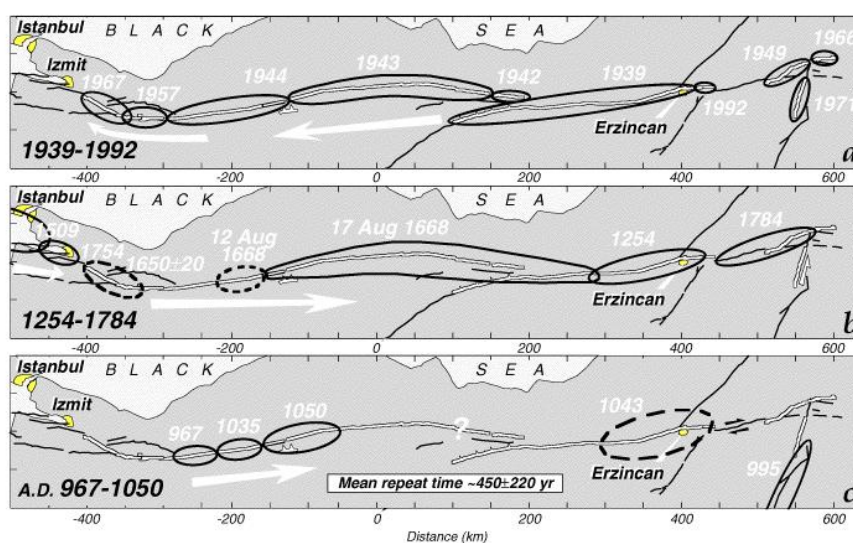


Fig. 7 17 Oct 96 Stein et al.

Earlier faulting sequences The North Anatolian fault has experienced several historical episodes of migrating earthquake sequences. Large earthquakes progressed ~ 250 km eastward during 967, 1035, and 1050 A.D.. A sequence ruptured perhaps 700 km of the fault during 1650 ± 20 to 1668. The locations of these ancient earthquakes have been reconstructed by combing historical accounts and plotting seismic intensity maps from the reported ground motions; they are therefore approximate.

Modelling the 1939–1992 sequence The change in Coulomb failure stress due to any earthquake can be calculated numerically, given the fault geometry, fault slip during the earthquake, and the driving stress. The diagram below shows cumulative stress changes caused by large earthquakes and steady deep slip on the North Anatolian fault since 1939. In each panel, the epicenter of the next earthquake to rupture is circled. All but the 1943 epicenter lie in regions where the stress rose significantly, typically by 2-5 bars, owing to the foregoing shocks and deep fault slip.

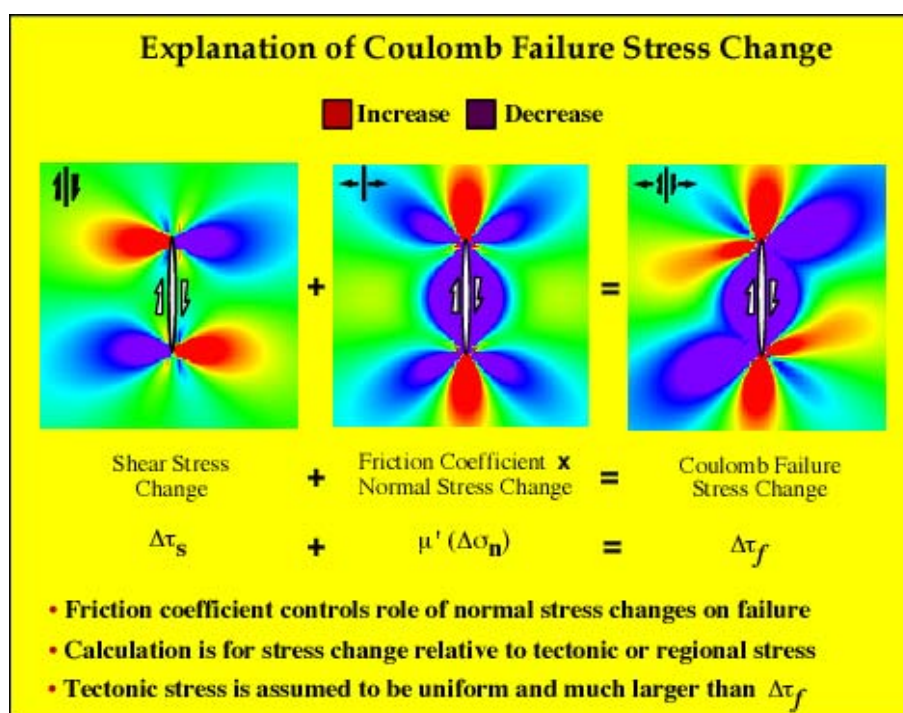
Izmit and Düzce earthquakes The 17 August 1999 $M_w = 7.4$ Izmit and 12 November 1999 $M_w = 7.1$ Düzce earthquakes killed 18,000 people, destroyed 15,400 buildings, and caused \$10–25 billion in damage. The Izmit earthquake occurred where the failure stress was previously calculated to have been increased by 1–2 bars (0.1–0.2 MPa) by the earthquake sequence since 1939. The Izmit event, in turn, increased the stress beyond the east

end of the rupture by 1-2 bars, where the Düzce earthquake struck, and by 0.5–5.0 bars beyond the west end of the Izmit rupture, where a cluster of aftershocks occurred.

Future Istanbul earthquake? Similar models suggest that the Izmit and Düzce earthquakes have increased the stress in the Istanbul region. The probability of strong shaking affecting Istanbul is calculated as $62 \pm 15\%$ (one standard deviation) during the next 30 years and $32 \pm 12\%$ during the next decade. Istanbul has been heavily damaged by earthquakes twelve times during the past 15 centuries; it appears that the city is in for another shock in the near future.

Why is the North Anatolian Fault unusually predictable? The North Anatolian fault zone has a simple, straight geometry, which makes for efficient transfer of stress. Its isolation from other major faults minimizes complicated stress transfer between competing faults. The en echelon fault strands tends to keep the entire fault from rupturing at once. In contrast, the San Andreas has not produced a coherent progression of earthquakes through space and time. It produces larger earthquakes along its smoother trace, and generally lies close to other major faults, making the stress transfer more complex and less predictable.

Information sources This account of is summarised from Stein et al. (*Geophysical Journal International*, v128, p594, 1997) and from Parsons et al. (*Science*, v288, p661, 2000); see <http://quake.wr.usgs.gov/research/deformation/modeling/papers/anatolia.html> and <http://quake.wr.usgs.gov/research/deformation/modeling/papers/istanbul.html>



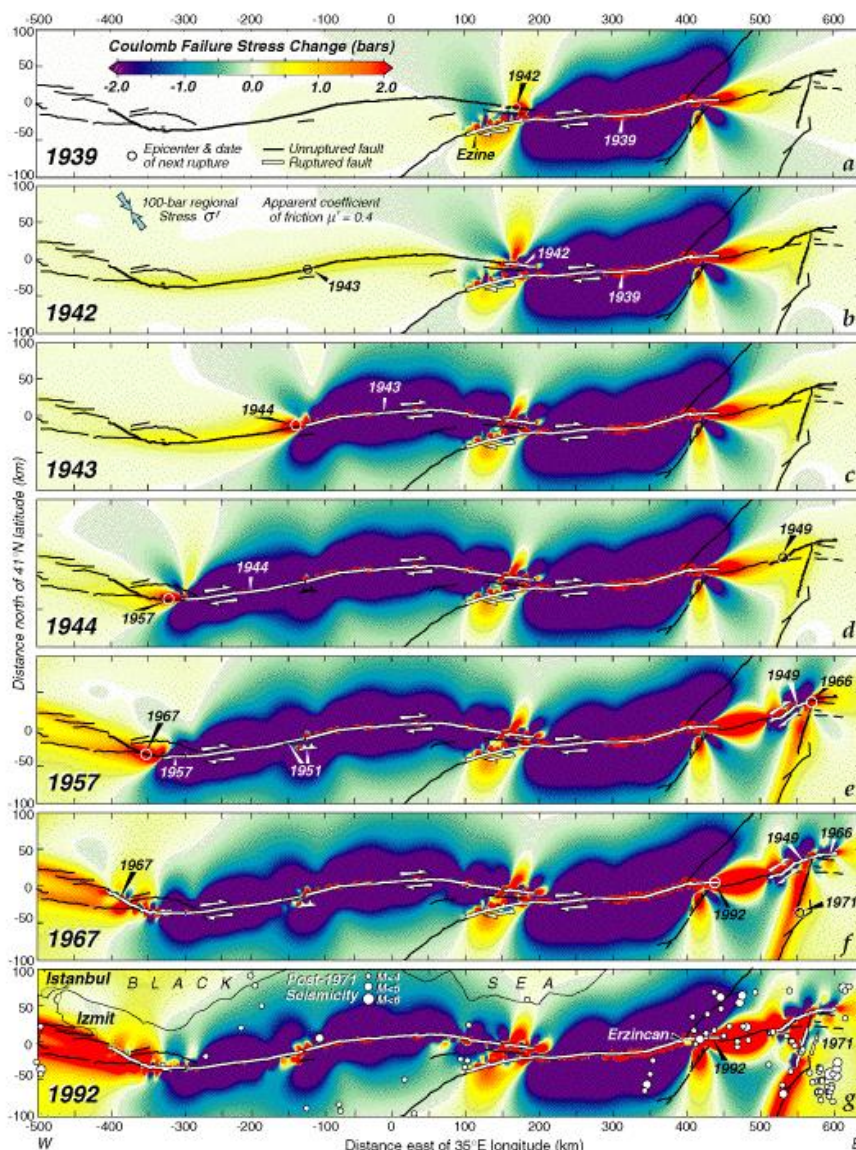


Figure 4 17 Oct 96 Stein et al.

Earthquake Mitigation: Base Isolators

One engineering strategy for reducing earthquake damage is to partially decouple a building from ground shaking in an earthquake. This strategy, called base isolation, is increasingly used to safeguard important structures. Building response recorded by the California Geological Survey in the 1994 Northridge earthquake (magnitude 6.7) confirmed the promise of the base-isolation strategy. The 8-story steel superstructure of the University of Southern California (USC) University Hospital in Los Angeles is supported by 149 isolators sitting on continuous concrete footings. During the Northridge earthquake, motions recorded at the top of the isolators and at the roof were less than those recorded in the ground below the isolators and at a nearby site removed from the building. The isolators reduced the level of motion fed into the base of the building by about two-thirds. The peak shaking at roof level was only about 40% of that recorded on the ground about 200 feet from the building, whereas with a conventional foundation

the roof-level shaking would have exceeded that measured on the ground. The result was that the hospital and its contents suffered no damage, despite the severe ground shaking produced by the quake.

Use of seismic isolation bearings permits the structure that they support to be less strong than would be required if the structure were to be firmly attached (through a conventional foundation) directly to the ground. This results in a lower cost and lower weight structure. For this reason, the employment of seismic isolation bearings is not only an efficient aseismic design strategy for new structures, but is an exceptionally effective method for the practical and economical retrofitting of structures that do not meet current seismic standards, or for which a higher degree of safety is desired.

